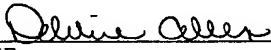


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APPLICATION FOR LETTERS PATENT

FOR

**POWER FACTOR CORRECTION CIRCUIT WITH HIGH-
VOLTAGE SEMICONDUCTOR COMPONENT**

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POWER FACTOR CORRECTION CIRCUIT WITH HIGH-VOLTAGE SEMICONDUCTOR COMPONENT

Cross Reference to Related Application

5 This application is a continuation in part of copending U.S. Patent Application Serial No. 09/786,022 filed November 9, 2001.

Technical Field

10 The present invention concerns the use of semiconductor compensation devices in power factor correction circuits.

Background of the Invention

 Such semiconductor devices are also known as compensation devices. Such compensation devices are, for example, n- or p-channel MOS field effect transistors, diodes, thyristors, GTOs, or other components. In the following, however, a field effect transistor (also referred to briefly as "transistor") is assumed as an example.

 There have been various theoretical investigations spread over a long period of time concerning compensation devices (cf. US 4,754,310 and US 5,216,275) in which, however, specifically, improvements of the on-resistance $R_{DS(on)}$ but not of stability under current load, such as, in particular, robustness with regard to avalanche and short circuit in the high-current operation with high source-drain voltage, are sought.

 Compensation devices are based on mutual compensation of the charge of n- and p-doped areas in the drift region of the transistor. The areas are spatially arranged such that the line integral above the doping along a line running vertical to

the pn-junction in each case remains below the material-specific breakdown voltage (silicon: approximately $2 \times 10^{12} \text{ cm}^{-2}$). For example, in a vertical transistor, as is customary in power electronics, p- and n-columns or plates, etc. may be arranged in pairs. In a lateral structure, p- and n-conductive layers may be stacked on each other
5 laterally alternating between a groove with a p-conductive layer and a groove with an n-conductive layer (cf. US 4,754,310).

By means of the extensive compensation of the p- and n-doping, the doping of the current-carrying region (for n-channel transistors, the n-region; for p-channel transistors, the p-region) can be significantly increased, whereby, despite
10 the loss in current-carrying area, a clear gain in on-resistance $R_{DS(on)}$ results. The blocking capability of the transistor depends substantially on the difference between the two dopings. Since, because of the reduction of the on-resistance, a doping higher by at least one order of magnitude of the current-carrying area is desirable, control of the blocking voltage requires controlled adjustment of the compensation level, which
15 can be defined for values in the range $\leq \pm 10 \%$. With a greater gain in on-resistance, the range mentioned becomes even smaller. The compensation level is then definable by

$$(p\text{-doping} - n\text{-doping})/n\text{-doping}$$

or by

20 charge difference/charge of one doping area.

Other definitions are, however, possible. Power factor correction circuits are used within switching power supplies and require special features within the switching element to provide high efficiency. Semiconductor switches according to the prior art usually generate a certain amount of heat through switching losses
25 which require the use of heat sinks and, thus, don't allow for small housings of the switching power supply.

Summary of the Invention

The present invention to provide a switching power supply including a robust semiconductor component of the kind initially mentioned, to be firstly distinguished by a high "avalanche" ruggedness and high current load capacity before
5 and/or during breakdown and secondly simple to produce with reproducible properties in view of technological latitudes of fluctuation of manufacturing processes. Thus, a very low on resistance can be guaranteed and, therefore, only a minimum of heat is generated in such a circuit. This allows for the use of a semiconductor switch without the requirement of a heat sink or at least a heat sink with only a small footprint.

10 A power factor correction circuit, thus, uses a semiconductor component of the kind initially mentioned, wherein the regions of the first and second types of conductivity are so doped that charge carriers of the second conductivity type predominate in regions near the first surface and charge carriers of the first conductivity type in regions near the second surface.

15 Preferably, the regions of the second conductivity type do not extend as far as up to the second zone, so that between said second surface and the second zone, a weakly doped region of the first conductivity type remains. It is possible, however, to allow the width of this region to go to "zero." The weakly doped region, however, provides certain advantages, such as enhancement of the barrier voltage, "smooth"
20 profile of the electrical field strength, or improvement of commutation properties of the inverse diode.

In another refinement, it is provided that between the first and second surfaces, a degree of compensation effected by the doping is so varied that atomic residues of the second conductivity type dominate near the first surface and atomic
25 residues of the first conductivity type near the second surface. In other words, there are sequences of p, p⁻, n⁻, n or n, n⁻, p⁻, p layers between the two surfaces.

A switching power supply including a power factor correction circuit comprises a rectifier having a positive and a negative output terminal, an inductor having a first and a second terminal, said first terminal being coupled with said positive output terminal, a semiconductor switch having a semiconductor body comprising a blocking pn junction, a gate electrode, a source zone of a first conductivity type connected to a first electrode and bordering on a zone forming the blocking pn junction of a second conductivity type complementary to the first conductivity type, and a drain zone of the first conductivity type connected to a second electrode, the side of the zone of the second conductivity type facing the drain zone forming a first surface, and in the region between the first surface and a second surface located between the first surface and the drain zone, areas of the first and second conductivity type nested in one another, wherein the areas of the first and second conductivity type are variably so doped that near the first surface doping atoms in the area of the second conductivity type predominate over those in the area of the first conductivity type, and near the second surface doping atoms in the area of the first conductivity type predominate over those in the area of the second conductivity type, wherein said second electrode is coupled to said second terminal of said inductor and said first electrode is coupled with the negative output terminal of said rectifier, a diode having an anode and a cathode, the anode being coupled with the second terminal of said inductor, a capacitor having a first and second terminal, said first terminal being coupled with the cathode of said diode and the second terminal being coupled with the first electrode of said semiconductor switch, an input current sensor generating a signal proportional to an input current, and a control unit having a first input and a second input and a control output coupled with said gate electrode, wherein said first input receives said signal from said current sensor and said second input is coupled with the first terminal of said capacitor.

Between the first and second surface the electrical field may have a rising course starting from both surfaces. A degree of compensation effected by

means of the doping in the areas of the first and second conductivity types may have a monotonic course between the first and second surface. The degree of compensation can also have a stepped course. The first conductivity type can be the n-conductivity type. The areas of the first and second conductivity type can be arranged vertically in the semiconductor body. In the areas of the second conductivity type a degree of compensation effected by means of doping can be varied such that near the first surface acceptor impurities dominate and near the second surface donor impurities dominate. The areas of the second conductivity type may have a roughly circular cross-section in a section parallel to the first surface and to the second surface and assume hexagonal surface packing. The areas of the second conductivity type may have a roughly circular cross-section in a section parallel to the first surface and to the second surface and assume roughly square surface packing. The areas of the second conductivity type may have a roughly strip-shaped cross-section in a section parallel to the first surface and to the second surface. The second surface can be positioned at a distance from the drain zone such that the regions of the first and second conductivity type nested in each other do not reach the drain zone. The input current sensor can be formed by an auxiliary source of said semiconductor switch. The semiconductor switch comprises a plurality of MOS transistors whose drains and gates are coupled in parallel wherein a main source is formed by the sources of a first set of said plurality of transistors coupled in parallel and the auxiliary source is formed by a second set of said plurality of transistors coupled in parallel. The input current sensor can be formed by a resistor coupled between the negative output terminal of said rectifier and the first electrode of said semiconductor switch. The control unit may comprise a ramp voltage generator coupled with said second input, a comparator receiving said ramp voltage, and a clock generator controlling said ramp voltage generator. The control unit may comprise a current to voltage converter generating an output voltage being fed to said comparator. The ramp voltage generator may comprise a transductance amplifier whose output signal charges a capacitance and a switch coupled in parallel with said capacitance being controlled by said clock

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generator. The switching power supply may further comprise a resistor coupled in parallel with said capacitor. The control unit may further comprise a gate driver coupled between said gate electrode and the output of said comparator.

5 The effect of the areas nested in each other, alternating different conductivity types, on the electrical field, is, in contrast to a conventional DMOS transistor, for example, as follows ("lateral" and "vertical" refer in the following to a vertical transistor):

10 (a) There is a cross-field, "lateral" to the direction of the connection between the electrodes, the strength of which depends on the proportion of the lateral charge (line integral perpendicular to the lateral pn-junction) relative to the breakdown charge. This field leads to the separation of electrons and holes and to a reduction in the current-carrying cross-section along the current paths. This fact is of primary significance for the understanding of the processes in avalanche, of the breakdown characteristic curve, and of the saturation region
15 of the output characteristics diagram.

(b) The "vertical" electrical field parallel to the direction of the connection between the electrodes is determined locally by the difference between the adjacent dopings. This means that with an excess of donors (n-loaded distribution: the charge in the n-conductive areas exceeds the charge of the
20 p-areas) on the one hand, a DMOS-like field distribution (maximum of the field on the blocking pn junction, decreasing field in the direction of the opposing back of the device) appears, whereby the gradient of the field is, however, clearly less than would correspond to the doping of the n-area alone. On the other hand, however, by overcompensation of the n-conductive area
25 with acceptors, a field distribution rising in the direction of the back is possible (p-loaded distribution: excess of acceptors compared to the donors). In such a

design, the field maximum lies at the bottom of the p-area. If the two dopings are exactly compensated, there is a horizontal field distribution.

With an exact horizontal field distribution, the maximum of the breakdown voltage is obtained. If the acceptors or the donors predominate, the breakdown voltage drops in each case. If the breakdown voltage is then plotted as a function of the degree of compensation, a parabolic characteristic is obtained.

Constant doping in the p- and n-conductive areas or even a locally varying doping with periodic maxima of equal height results in a comparatively sharply pronounced maximum of the "compensation parabola". For the benefit of a "production window" (including the fluctuations of all relevant individual processes), a comparatively high breakdown voltage must be steered for in order to obtain reliable yields and production reliability. Consequently, the objective must be to make the compensation parabola as flat and as broad as possible.

When the blocking voltage is applied to the device, the drift region, i.e., the region of the areas of opposite doping arranged in pairs, is cleared of mobile charge carriers. The positively charged donor cores and the negatively charged acceptor cores remain in the spreading space charge region. They then determine the course of the field.

The flow of current through the space charge region causes a change in the electric field when the concentration of the charge carrier associated with the flow of current comes into the region of the background doping. Electrons compensate donors; holes compensate acceptors. For the stability of the device, it is also very important which doping predominates locally, where charge carriers are generated, and how their concentrations result along their current paths.

For the following embodiments, for an understanding of the basic mechanism, initially a constant doping of the p- and n-conductive areas is assumed.

In the on-state and especially in the saturation region of the output characteristics of a MOS transistor, a pure stream of electrons flows from the channel into an n-doped area, also referred to as a "column" in a vertical transistor, whereby in the base an increasing focusing of the flow of current occurs because of the electrical cross-field. High-current stability is promoted by dominance of the n-doping; however, since the channel region with its positive temperature coefficient eliminates inhomogeneous current distribution in a cell field, this mode of operation is rather uncritical. Reduction in the current density is obtained through partial shadowing of the channel connection (cf. DE 198 08 348 A1).

With regard to the breakdown characteristic or its course, the following must be taken into consideration: The generation of electrons and holes occurs in the region of maximum field strength. The separation of the two types of charge carriers is performed by the electrical cross-field. Along the two current paths in the p- and n-area, respectively, focusing and further multiplication occurs. Ultimately, also no effect of a partial channel shadowing occurs. Stability is present only when the mobile charge carriers cause a rise in the electrical field outside their source and thus a rise in the breakdown voltage of the respective cell. For compensation devices this means stability in the p- and n-loaded region, but not in the maximum of the compensation parabola. In the p-loaded region, the breakdown occurs at the "bottom" of the column. The electrons flow out of the drift region and thus do not affect the field. The holes are pulled through the longitudinal electrical field to the top source contact. In the process, the hole current is focused along its path by the electrical cross-field: The current density rises here. Thus, the longitudinal electrical field is initially affected near the surface. As a result of compensation of the excess acceptor cores (p-loaded distribution), a reduction in the gradient of the electrical field and a rise in the breakdown voltage occur. This situation is stable as long as the field there remains clearly below the critical field strength (for silicon: approximately 270 kV/cm for a charge carrier concentration of approximately 10^{15} cm^{-3}).

In the n-loaded region with an excess of donors, the breakdown is near the surface. The holes flow to the source contact and still affect the field on their path from their source to the p-well. The objective must consequently be to place the breakdown location as near as possible to the p-well. This can be accomplished, for example, by a local elevation in the n-doping. The electrons flow through the complete drift zone to the back and likewise affect the field along their current path. Stability is obtained when the effect of the electron current prevails over that of the hole current. Since the geometry of the cell arrangement plays an important role here, there is a region of stable and instable characteristic curves especially near the maximum of compensation parabola.

The conditions in the avalanche are very similar to those of a breakdown. The currents are, however, clearly higher and have with a rated current as much as twice the rated current of the transistor. Since the electrical cross-field always causes a clear focusing of the current, in compensation devices the stability range is left at comparatively low current loads. Physically, this means that the current-induced rise in the field has already advanced so much that locally the breakdown field strength has been reached. The longitudinal electrical field can then not rise further locally; the curvature of the longitudinal electrical field, however, increases which results in a drop in the breakdown voltage of the cell in question. In the characteristic curve of an individual cell and also in the simulation, this is reflected by a negative differential resistance; i.e., the voltage drops as the current rises. In a large transistor with more than 10,000 cells this results in a very rapid inhomogeneous redistribution of the current. A filament is formed, and the transistor melts locally.

This yields the following consequences for the stability of compensation devices:

- (a) Due to the separation of electrons and holes there is no "auto-stabilization" as with IGBTs and diodes. Instead, the degree of compensation, field distribution, and breakdown location must be set exactly.

- (b) On the compensation parabola, with constant doping of the p- and n-areas or "columns", there are stable regions in the clearly p- and in the clearly n-charged regions. The two regions are not contiguous. Thus, there is only an extremely small production window. With constant doping of the p- and n-areas or columns, the compensation parabola is extremely steep. The breakdown location moves within a few percent from the bottom of the p-column in the direction of the surface.
- (c) For each compensation device, there is a current destruction threshold in the avalanche which is directly coupled with the degree of compensation. The degree of compensation, on the other hand, determines the achievable breakdown voltage and effects the $R_{DS(on)}$ gain.
- (d) With constant doping of the p- and n-areas, the devices are -- as mentioned above -- instable near the maximum of the compensation parabola. This results in the fact that the devices with the highest blocking voltage are destroyed in the avalanche test .

As explained above, to prevent the disadvantages, the degree of compensation is varied along the doping areas, i.e., in a vertical structure from the top in the direction of the back of the transistor, such that the atomic cores of the second conductivity type dominate near the surface and the atomic cores of the first conductivity type dominate near the back.

The resultant field distribution has a "hump-shaped" curve with a maximum at approximately one-half of the depth(cf. Fig. 6). Thus, both the electrons and holes affect the field distribution in the breakdown and in the avalanche. Both types of charge carriers have a stabilizing effect, since in each case they run from their source into areas in which they compensate the dominating excess background doping. There is thus a continuous stability range from p-loaded to n-loaded degrees of compensation.

A variation of the degree of compensation due to production fluctuations shifts the breakdown location only slightly in the vertical direction and continuously back and forth, as long as this variation is less than the technically adjusted variation of the degree of compensation. The size of this modification of the
5 degree of compensation also determines the limits of the stability range. Thus, the production window becomes freely selectable.

The focusing of the currents is clearly less pronounced since both types of charge carriers travel only one-half the path in the region of the compressing electrical cross-field. Thus, the devices can be stressed with clearly higher currents in
10 the avalanche.

Since in a variation of the degree of compensation, e.g., in the direction toward "n-loading", the electrical field increases in each case in the upper area of the drift region, but simultaneously decreases in the lower area (vice versa with variations toward p-loaded distribution), the breakdown voltage varies only relatively little as a
15 function of the degree of compensation. Thus, the compensation parabola becomes preferably flat and wide.

The vertical variation of the degree of compensation can be effected by variation of the doping in the p-region or by variation of the doping in the n-region or by variation of the doping in both regions. The variation of the doping along the
20 column may have a constant rise or be in a plurality of steps. In principle, the variation increases monotonically from a p-loaded degree of compensation to an n-loaded degree of compensation.

The invention can be readily applied even with p-channel transistors. In that case, an appropriately altered course of the semiconductor regions occurs: A (p,
25 p-dominated, n-dominated, n) course is replaced by an (n, n-dominated, p-dominated, p) course.

The stability limits are reached on the n-loaded side when the field runs horizontally near the surface over an appreciable part of the drift region. On the p-loaded side the stability limits are reached when the field runs horizontally near the bottom of the compensating column region over a noticeable part of the drift region.

5 In general, the compensation parabola becomes flatter and wider the greater the gradient of the degree of compensation. The breakdown voltage in the maximum of the compensation parabola drops accordingly.

 Another important limitation of the variation of the degree of compensation results from the requirement to remain below the breakdown charge. In
10 addition, with greater elevation of the p-column doping near the surface, current pinch-off effects occur near the surface (lateral JFET effect).

 For 600 V devices, a variation of the degree of compensation lengthwise of the p- and n-areas of 50 %, for example, is advantageous.

 Although above the starting point has been primarily a vertical
15 transistor, the semiconductor device according to the invention can, in principle, have a vertical or even a lateral structure. With a lateral structure, n- and p-conductive plate-shaped areas are, for example, arranged laterally stacked in each other.

 Applications for such lateral transistors are, for example, found in the smart power sector or in microelectronics; vertical transistors are, in contrast,
20 produced primarily in power electronics.

 The vertical modification of the degree of compensation is very simple to implement since in the individual epitaxial planes, only the implantation dose must be altered. The "real" compensation dose is then implanted in the middle epitaxial layer; below that, for example, 10 % less in each case, above that, for example, 10 %
25 more in each case. However, instead of the implantation dose, it is possible to alter the epitaxial doping.

By means of the more manageable variation, it is possible to reduce the production costs. The number of necessary epitaxial layers can be reduced, and the openings for the compensation implantation can be reduced as a result of greater variation of the implanted dose due to the greater relative variation of the resist dimension with simultaneously prolonged subsequent diffusion for the merging of the individual p-regions into the "column".

The structure according to the invention is produced by the following individual steps:

First, a multi- μm -thick, n-doped epitaxial layer is applied to a semiconductor substrate. The p-doping ions are introduced into this epitaxial layer via a resist mask by means of ion implantation. Next, the entire process is repeated as often as necessary until there is an adequately thick n-multi epitaxial layer with embedded p-centers aligned with each other and stacked. The production of the actual device then occurs, by means of, for example, the processing of the base zones, the source zones, the front metalization, and the gate electrodes in a field effect transistor. By thermal diffusion, the p-doped centers merge into a rippled vertical column. Due to intrinsic compensation, the concentration of the p- or n-doping material is always substantially higher than the resultant electrically active doping.

The ripple of the vertical column is expressed in a varying acceptor-donor ratio $k_e(z)$ per horizontal plane. The electrical compensation varies accordingly in each horizontal plane in the semiconductor body. The ripple of the column causes no significant change in the horizontal field. Consequently, in the first approximation, the contribution U_{Bh} is considered unaffected by the ripple.

In the vertical direction, layers with non-horizontally compensated p-and n-charges alternate. An epitaxial layer corresponds to a complete ripple period and, consequently, corresponds to two adjacent pn-junctions. Due to the production

fluctuations in the epitaxy cycles, the charge balance is not equalized over the entire volume of a pn-junction such that the degree of compensation does not equal 0.

In a semiconductor device according to the present invention, the voltage consumed in the blocked state in the cell field between anodes and cathodes or
5 in a field effect transistor vertically between source and drain must also be discharged laterally on the edge of the semiconductor device. Semiconductor devices are often operated up to a breakdown. In this case, a very high current flows through the impact ionization which occurs. In order not to destroy the semiconductor device, no excessively high current densities may occur, i.e., the breakdown current must be
10 distributed as uniformly as possible over the entire semiconductor device. However, this requirement can be fulfilled only if the cell field carries the majority of this current. If the semiconductor device breaks down in the edge structure at a smaller blocking voltage than the cell field, this results in most cases in irreversible thermal damage to the semiconductor device. The semiconductor device must, consequently,
15 be avalanche-rugged. Avalanche-rugged semiconductor devices, especially vertical transistors, reduce the safety distance necessary to manage overvoltages, whereby in many applications comparatively low-blocking transistors may be used, which require at the same $R_{DS(on)}$ a comparatively small semiconductor device surface and are thus more economical. With conventional high-voltage MOSFETs, this is very significant
20 since the $R_{DS(on)}$ of these transistors rises disproportionately with the breakdown voltage. With conventional power devices, expensive surface-mounted structures or structures near the surface usually result in the situation that the semiconductors device edge can block more voltage than the cell field. The lower-lying semiconductor device volume is homogeneously doped so low that it withstands the necessary
25 voltage without structuring. With the semiconductor devices according to the present invention, which use the production process of intrinsic compensation, the demands with regard to the edge structure are intensified because here even the lower-lying volumes under the edge must be processed. The material actually accommodating the

blocking voltage, i.e., the epitaxial layer above the highly doped semiconductor substrate, is relatively low ohmic and will only block a fraction of the required voltage. The blocking capability for the cell field is achieved only with the introduction of the counter doped columns.

5 For the volume below the edge, there are, in principle, two different processing methods:

1. The semiconductor edge may be processed separately from the cell field, i.e., in additional steps. An overall counter doping of the substrate on the semiconductor edge, e.g., by means of overall edge implantation and diffusion,
10 is conceivable. Thus, an overall intrinsically compensated and thus highly blocking edge can be produced. Such a procedure is, however, associated with very high costs.
2. The column structure in the cell field is continued into the edge, whereby the substrate is also built up to basically the same blocking voltages as in the cell
15 field. A minimal increase, for example, in the dielectric strength of the edge may be obtained in many cases by means of a suitable variation of the deep compensation profile of the columns, as this has been described on the preceding pages for the cell field, whereby, however, the tolerance range
20 compared to the cell field and thus the tolerance range of the entire semiconductor device becomes smaller. Additionally, additional effects may provoke breakdown on the edge of the semiconductor device.

On the one hand, the surface-mounted edge structures or structures near the surface cause additional field distortions and generate centers of high field strength.

25 On the other hand, it may be necessary to apply an expedient negative "error charge" to the edge, which causes a curvature of the equipotential lines toward the semiconductor device surface, whereby these can be picked up and carried by the

surface structure. This corresponds to a field discharge on the semiconductor device edge. This error charge condition may also cause a voltage-induced premature breakdown of the semiconductor device edge compared to the cell field.

Accordingly, it is best to reduce the horizontal components of electric
5 field and simultaneously the vertical ripple of the compensation profile on the edge. Both result in higher blocking voltages on the semiconductor device edge. To implement this, the local separation must be eliminated or at least weakened in the charge centers of opposing polarity, i.e., an intrinsic compensation must be undertaken.

10 Thus, a high-voltage resistant edge structure is created, which consists of a plurality of floating zones of the second conductivity type, which are separated by intermediate zones of the first conductivity type, whereby the width of the intermediate zones and width of the floating zones are smaller than the width of the areas of the first and of the second conductivity type, which are nested in each other
15 inside the cell fields. These floating zones and intermediate zones are doped such that the charge carriers of floating zones and of intermediate zones are completely cleared with the application of blocking voltage.

Thus, preferably, the edge volume is processed in one and the same operation, whereby both the thickness of an individual epitaxial layer and the cell grid
20 is reduced in size in the edge region, yielding at the end of the process homogeneous dopant distribution for both types of charge carriers for each edge cell. With regard to the ratio of unmasked surface per cell to the total cell surface in the edge region, the charge applied by implantation can be ideally adapted to the charge which is defined by the epitaxy. In order to achieve ideal blockability, a charge balance, i.e.,
25 intrinsically compensated condition, is sought.

Preferably, the thickness of the individual epitaxial layers will be designed according to specifications which the cell field defines. This again yields a

vertically rippled compensation profile on the semiconductor edge, but in a substantially weaker form than in the cell field. A reduction in the cell grid results in the fact that the resolution of the doping material source is reduced, whereby the boundaries of the individual diffusion fronts become blurred.

- 5 An additional advantage of the edge design described is the coupling between the production defects in the edge and in the cell field since error mechanisms act in both regions in the same direction.

Brief Description of the Drawings

- 10 The invention is explained in detail in the following with reference to the drawings. They depict:

Fig. 1 a top view of an n-channel lateral MOS transistor according to a first exemplary embodiment of the invention,

- 15 **Fig. 2** a cross-section of an n-channel lateral MOS transistor with V-shaped grooves according to a second exemplary embodiment of the invention,

Fig. 3a through 3d various layouts in the semiconductor device according to the invention,

Fig. 4 a cross-section through an n-channel lateral MOS transistor according to a third exemplary embodiment of the invention,

- 20 **Fig. 5** the course of the degree of compensation K along the line C-D in Fig. 4,

Fig. 6 the course of the electrical field along the line C-D in Fig. 4,

Fig. 7 the course of the breakdown voltage as a function of the degree of compensation for constant doping and for variable doping,

Fig. 8 a concrete example of the cell design for an n-channel MOS transistor,

Fig. 9a through 9c various square edge structure layouts in the semiconductor device according to the invention,

Fig. 10a through 10c various strip edge structure layouts in the semiconductor device according to the invention,

Fig. 11 a hexagonal edge structure layout in the semiconductor device according to the invention,

Fig. 12 a cross-section through an n-channel MOS transistor according to a fourth exemplary embodiment with an edge structure layout,

Fig. 13 a cross-section through an n-channel MOS transistor according to a fifth exemplary embodiment with a different edge structure layout,

Fig. 14 shows an exemplary embodiment of a power factor correction circuit using a semiconductor switch formed by a compensation device,

Fig. 15 shows an exemplary embodiment of a control unit as shown in Fig. 14,

Fig. 16 shows an exemplary embodiment of a ramp voltage generator as shown in Fig. 15,

Fig. 17 shows another exemplary embodiment of a power factor correction circuit using a semiconductor switch formed by a compensation device, and

Fig. 18 shows relevant parts of yet another exemplary embodiment of a power factor correction circuit using a semiconductor switch formed by a compensation device.

Detailed Description of the Preferred Embodiments

Fig. 1 depicts a top view of an n-channel MOS transistor with an n^+ -conductive drain zone 15, an n^+ -conductive source zone 16, a gate electrode 8, and a p-conductive area 5. This p-conductive area 5 extends finger-like into an n-conductive area 4 on a semiconductor substrate 1, such that the areas 4 and 5 are "nested" in each other. The gate electrode 8 may, for example, be made of polycrystalline silicon, whereas an isolation layer not shown in Fig. 1 below this gate electrode 8 is made, for example, of silicon dioxide and/or silicon nitride. In the p-conductive area 5, a p-charge excess is present in a zone I; a "neutral" charge, in a zone II; an n-charge excess, in a zone III. This means that in the area 5 in the zone I, the p-charge dominates the charge of the surrounding n-conductive area 5; that also in the zone II, the p-charge exactly compensates the charge of the surrounding n-conductive area 5; and that in the zone III, the p-charge is less than the charge of the surrounding n-conductive area 5. It is thus significant that the charge of the p-area 5 is variable whereas the charge of the n-areas 4 is in each case constant.

The p-conductive area 5 extends from the edge of the source zone 16, i.e. from a surface A to a dashed line surface B in the n-conductive region 4. This surface B is positioned at a distance from the drain zone 15, such that there is, between the surface B and the drain zone 15, an n-conductive region 13 in which there is no "nesting" with p-conductive regions 5. However, it is also possible to shift the surface B to the edge of the drain zone 15, such that there is no n-conductive region 13. Advantageously, however, the surface B is positioned at a distance from the drain electrode 15, which results in an increase of the blocking voltage, a smoother course of the electrical field, and an improvement of the commutating characteristics of the inverse diode.

Fig. 2 depicts a cross-section through another exemplary embodiment of the semiconductor device according to the invention in the form of an n-channel

MOS transistor with a drain electrode 2 and a gate insulation layer 9 between the gate electrode 8 and the channel region, which is provided under the insulation layer 9 between a source zone 16 and a drain zone 15 in a p-conductive region 5. Also, in this exemplary embodiment, the p-conductive areas 5 in the zones I, II, and III have variable doping, as was explained above with reference to Fig. 1.

The exemplary embodiments of Fig. 1 and 2 depict two preferred design possibilities for lateral structures of the semiconductor device according to the invention. Essential in the two structures is the fact that the reported variable doping is present in the areas 5 and that these areas 5 do not reach the drain zone 15, i.e., terminate in a surface B at a distance from this drain zone 15. However, it is possible to move the surface B toward the edge of the drain zone 15. As stated above, the degree of compensation can be obtained by variation of the doping of the p-conductive areas 5 or of the n-conductive areas 4.

Fig. 3a through 3d depict various layouts for the semiconductor device according to the invention with hexagonal polysilicon structures 17 and polysilicon openings 18 (Fig. 3a), in which aluminum contact holes 19 (Fig. 3b) may be provided. Fig. 3c depicts a layout with rectangular polysilicon structures 20 and corresponding polysilicon openings 18 and aluminum contact holes 19, whereas Fig. 3d schematically depicts, in a top view and in cross-section, a strip structure with polysilicon gate electrodes 8 and aluminum electrodes 21.

Fig. 3a through 3d depict how the semiconductor device according to the invention can be designed with different structures.

Fig. 4 depicts a cross-section through an n-channel MOS transistor with an n⁺-conductive silicon semiconductor substrate 1, a drain electrode 2, a first n-conductive layer 13, the second layer 3 with n-conductive areas 4 and p-conductive areas 5, p-conductive zones 6, n-conductive zones 7, gate electrodes 8 made, for example, from polycrystalline silicon or metal, which are embedded in an isolating

layer 9 made, for example, from silicon dioxide, and a source metalization 10 made, for example, from aluminum. Here again, the p-conductive areas 5 do not reach the n^+ -conductive semiconductor substrate.

For the sake of clarity, Fig. 4 depicts only the metal layers hatched, although the remaining areas or zones are also depicted in cross-section.

In the p-conductive areas 5, there is a p-charge excess in a zone I, a "neutral" charge in the zone II, and an n-charge excess in zone III. This means that in the area 5 which forms a "p-column" in the zone I, the charge of the p-column dominates the charge of the surrounding n-conductive area 5, further that in the zone II, the charge of the p-column precisely compensates the charge of the surrounding n-area 5, and that in the zone III, the charge of the p-column does not yet dominate the charge of the surrounding n-area 5. It is also essential that the charge of the p-areas 5 is variable, whereas the charge of the n-areas 4 is in each case constant. However, it is possible here, as in the preceding exemplary embodiments, that the charge of the p-conductive areas 5 is constant and the charge of the n-conductive areas is varied. It is likewise possible to design the charge variable in both areas 4 and 5.

Fig. 5 depicts in a cross-section C-D the course of the degree of compensation K over the depth t of the n-channel MOS transistor: As is discernible from Fig. 5, the degree of compensation K rises monotonically with a constant gradient or in steps from the point C to point D.

It is discernible from Fig. 6 that the electrical field E has a substantially constant curvature over the area 5 between the points C and D.

Fig. 7 depicts compensation parabolas for a constant and a variable doping of the p-conductive areas 5 in the exemplary embodiment of Fig. 4. The degree of compensation K is plotted in percentages on the abscissa, whereas the ordinate indicates the breakdown voltage U in volts. One curve 11 depicts the breakdown voltage U for a variable doping, whereas a curve 12 depicts the breakdown voltage for

a constant doping. It is clear that the variable doping brings a considerable drop in the breakdown voltage from approximately 750 V to approximately 660 V. However, in exchange, a larger range of the degree of compensation can be used.

Fig. 8 depicts finally a cell design in a cross-section with a drain D, a source S, and a gate G, the n^+ -conductive semiconductor substrate 1, an n-conductive semiconductor region 13, the n-conductive layer 3, and n-conductive regions 4 as well as p-conductive regions 5 for the p-conductive region 5 under the source electrode S. In Fig. 8 the degrees of compensation, for example, between + 30 % and - 20 % are reported, whereby a degree of compensation "0" indicates true compensation between n-doping and p-doping. Here, the doping thus varies within the "p-column" by a factor 3 whereas the doping in the "n-columns" is constant.

Fig. 9a through 9c depict, in principle, as in Fig. 3a through 3d, how the semiconductor device according to the invention can be designed with different structures which extend into the edge region. As can be discerned in Fig. 9a through c, Fig. 10a through c and in Fig. 11, in the semiconductor edge region, a large number of floating zones 5', are formed from the second conductivity type and are separated from intermediate zones 4' of the first conductivity type. The width of the intermediate zones 4' and the widths of the floating zones 5' are smaller than the widths of the regions 4, 5 inside the cell field. The floating zones 5' and the intermediate zones 4' are dimensioned such that their charge carriers are completely cleared with the application of blocking voltage. The zones 5', which are designed lightly p-doped in the present exemplary embodiment, are "floating", i.e., they have an undefined potential. The floating zones 5' are positioned at a distance from each other, whereby the region between the floating zones 5' defines an intermediate zone 4'. This intermediate zone 4' typically has the same doping concentration as the doping in the zones 4 within the cell field.

Fig. 9a, b, and c depict different variations of the widths of the floating zones compared to the basic widths in the cell field. Fig. 10a, b, and c depict the same

thing with the strip edge structure layout and Fig. 11 with a hexagonal edge structure layout.

Fig. 12 and Fig. 13 depict the n-channel MOS transistor known from Fig. 4, which has been expanded by an intrinsically compensated edge termination.

5 The transistor is built in known fashion with an n^+ -conductive silicon semiconductor substrate 1, a drain electrode 2, a first n-conducting layer 13, a second layer with n-conducting areas 4 and p-conductive areas 5, p-conductive zones 6, n-conductive zones 7, gate electrodes 8 made, for example, from polycrystalline silicon or metal, which are embedded in an insulation layer 9 made, for example, from silicon dioxide,

10 and a source metalization 10 made, for example, of aluminum. In the present figures in each case two p-conductive areas 5 and n-conductive areas 4 are depicted on the left side. Toward the right, additional p-conductive areas 5' and n-conductive areas 4' extend alternately. The p-conductive areas 5' have, compared to the p-conductive areas 5, roughly half the width; however, they extend roughly as far into the

15 n-conductive region 13 in the direction of the substrate 1. The regions 5', 4' lying adjacent the regions 4, 5 are connected to a p-conductive zone 6', which connects via a contact hole with the source metalization 10. The p-conductive zone 6' forms a p-ring known from the prior art. The p-conductive zones 6' has, in contrast to the cell field, no n-conductive zone, to prevent parasitic transistors. The n- and p-conductive areas

20 4', 5' extend far beyond the p-conductive zone 6' in the direction of the edge of the device. On the outermost edge, there is a so-called channel stopper configuration, which consists of a gate electrode 8', which is electrically connected with an n-conductive zone 7'', which for its part is accommodated in a p-conductive zone 6'' in the n-conductive region 13.

25 The so-called space charge region stopper depicted in Fig. 13 constitutes an alternative to the channel stopper configuration depicted in Fig. 12. This space charge region stopper consists only of a well conductive n^+ -conductive zone, which is placed in the n-conductive region.

Common to both exemplary embodiments is the fact that the contact holes of the p-conductive zone 6' are substantially larger compared to the contact holes in the n- or p-conductive zones 7, 6. The result of this is that the gate electrode 8', which lies above the areas 4', 5' is designed substantially smaller compared to the gate electrodes 8 of the cell field. The grid, in which the areas 4', 5' are arranged, is roughly half as large as the areas 4, 5 of the cell field.

The compensation device (power transistor) according to the present invention can be used in many application. In particular beneficial is the use of such a compensation device in a power factor correction circuit within a switching power supply. Such a switching power supply is used for energy conversion which receive an AC voltage and provide a DC voltage having a predefined level. Object of such a converter is to form the current in such a way that it follows the form of the AC input voltage. As a result, the converter acts like a resistive load, such as a resistor and the power factor results as close to the ideal value of 1 as possible. The power factor correction circuit can produce currents with equal form but with different peak values. Thus, the circuit is able to generate currents of different values and, therefore, can hold the DC output voltage constant even when the load requires different levels of power. To this end, a power transistor is used as switch within the circuit which is relatively high clocked with respect to the incoming AC voltage and only a relatively small inductance is needed.

Fig. 14 shows an exemplary application of a power compensation device according to the present invention with respect to such a circuit 1400. The AC voltage can be applied to input terminals 1405 and 1406 and is fed to a rectifier 1401, 1402, 1403, 1404. the positive output of the rectifier is coupled with the first terminal of an inductance 1407. The second terminal of inductance 1407 is coupled with a first terminal of a diode 1408 and the drain of a power compensation device 1410. The second terminal of diode 1408 is coupled with the first terminal of a capacitor 1409,

the first terminal of a resistor 1411, a first input of a control unit 1412 and an output terminal 1413.

In one embodiment, the negative output of the rectifier is coupled a first terminal of a shunt resistor 1415. The second terminal of resistor 1415 is coupled
5 with the source of compensation device 1410, the second terminal of capacitor 1409, the second terminal of resistor 1411, a second output terminal 1414, and with a second input of control unit 1412. However, as will be described below, the shunt resistor is not necessary in other embodiments. Also, in other embodiments with a shunt resistor, the first terminal of the shunt resistor might be used for coupling with
10 the second input of control unit 1412. A control output of control unit 1412 feeds a control signal to the gate of compensation device 1410.

Fig. 15 shows an exemplary embodiment of the control unit 1412 in more detail. Such a control unit comprises a clock generator 1510 which generates a high frequency clock signal, such as for example 300 kHz. A ramp voltage generator
15 receives the output voltage at the output terminal 1413 through a terminal 1570. The ramp voltage generator is reset by the clock signal generated by clock generator 1510. The resulting periodic ramp voltage is fed to the positive input of a comparator 1540. The negative input of comparator 1540 receives the output voltage of a current to voltage converter 1530 which receives an input current from the switching power supply. If the switching power supply already provides a voltage proportional to the
20 input current, no current/voltage converter 1530 is needed. The output signal of comparator 1540 is fed to a gate driver 1550 which generates the appropriate gate control voltage for opening or closing the switch formed by power compensation device 1410. The control unit according to this embodiment evaluates the input
25 current and the output voltage of the switching power supply. However, if necessary, additional parameters can be used to provide a control signal for the switch, such as for example, the input voltage.

Fig. 16 shows some more exemplary details of the control unit. Similar elements have similar numerals. The ramp voltage generator can be formed by a transductance amplifier 1600 which transforms the input voltage at terminal 1570 into an output current. This output current charges a capacitance 1610. Thus, depending
5 on the level of the output voltage the slope of a respective voltage across the capacitance 1610 will vary. A switch 1620 is used to provide a reset function by discharging the capacitance 1610. The clock signal generated by clock generator 1510 controls switch 1620. The voltage across the capacitance is fed to the positive input of comparator 1540. In this embodiment, it is assumed that a voltage proportional to
10 the input current, for example the voltage across a resistor 1415 is provided by the circuit. This voltage can be fed to a resistor divider 1630 and 1640 through terminal 1580. The resistor divider 1630, 1640 provides an adjusted voltage to the negative input of comparator 1540.

Fig. 17 shows another embodiment using a different type of
15 compensation device type. Similar elements are designated by similar numerals. This embodiment does not require a resistor 1415 between the rectifier and the switch 1700. The switch 1700 is formed by a compensation device as described above having an auxiliary source terminal which outputs a current proportional to the current through the drain source path. This current is very small compared to the main current
20 and can thus be used as a sensor signal.

Fig. 18 shows parts of yet another embodiment similar to the embodiment shown in Fig. 17. The compensation device is formed by a plurality of compensation devices whose drain electrodes and gate electrodes are coupled in parallel. Two sets of the plurality of compensation devices form substantially two
25 transistors whose drain and gate electrodes are connected in parallel. The first set represents the main compensation device 1800 and the second set represents the auxiliary compensation device 1801. All the source electrodes of the first set of compensation devices are connected in parallel. Similarly, the source electrodes of the

second set are connected in parallel to form an auxiliary source electrode. The ratio of number of compensation devices of the first set compared to the second set depends on the required output proportion. The auxiliary compensation device will thus generate an output current proportional to the main compensation device.

5 Using a power compensation device 1410 as described in detail in this disclosure as a switch in combination with a power factor correction circuit can be in particular beneficial. Operating the power factor correction circuit in a discontinuous mode, in which the current decreases to zero before the switch is re-activated, only the turn-off losses and the conduction losses created by the switch will be relevant. The
10 turn on loss can be neglected because the switch is turned on when no current is present. During the discontinuous mode, particular high peak currents appear due to a triangular current shape within the switch. This current creates and burdens the switch with lost heat with $P = I^2 * R_{on}$. Thus, a switch with a minimum on resistance R_{on} will be highly beneficial in such a circuit. A power compensation device using the
15 compensation principles as described in this disclosure allows for a very low on resistance R_{on} and, thus, fulfills this requirement. To reduce the turn off losses, a particularly fast switch off process within the switching transistor is necessary. The power factor correction circuit includes a free running diode which will act on any peak voltages created by the switch due to parasitic inductances in the path to the
20 switch. Therefore, there will be no risk of an avalanche effect and the switch can be turned off as quickly as possible. The described power compensation device is able to perform in such a way because of its smaller device capacities due to a small chip area and because of the non-linear course of the output capacitance. Contrary to a MOSFET according to the state of the art, the p-columns in the described
25 compensation device contribute to a fast expansion of the space charge region. This leads to a very quick decline of the gate-drain and drain-source capacitances to very small values. As soon as the p- and n-columns reciprocally deplete, the drain-source-capacitance will diminish drastically due to the surface depletion. Thus, compared to

regular MOS field effect transistors, a compensation device as described in this disclosure reaches extremely short switch off times due to the substantially lower capacitances.

In case of operating the power factor correction circuit in a continuous current mode, in which the current through the inductivity 1407 does not decrease to zero when the switch 1410 is turned on again, and the current through the switch 1410 has a trapezoidal form, the turn on process includes beside the load current through the inductivity 1407 the charge stored in the diode 1408. In this mode, the turn on losses have to be considered. Again, the compensation device as disclosed has a particular fast switch on time such as in the range of a few nanoseconds due to the smaller chip area and, thus, smaller capacitances. Furthermore the space charge region, which is completely depleted of mobile carriers during the blocking (turned off) phase of the switch, is neutralized during turn on by the electron current from the MOS channel and a hole drift current from the p-well. In contrast to a conventional MOSFET where the space charge region is neutralized only by the MOS channel current, we have in a compensation device a second drift current consisting of holes, which helps to neutralize the space charge region in a quick and effective manner. Due to this principle a much faster turn on time of the switch can be accomplished.

The combination of the control principles of a power factor correction circuit benefits, therefore, in particular from the use of a compensation device as described in this disclosure and leads to a highly efficient power factor correction circuit with a high degree of efficiency and an easy control mechanism using only the output voltage and the input current of the switching power supply.